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IMPROVED ESTIMATION PROCEDURES FOR ITEM RESPONSE
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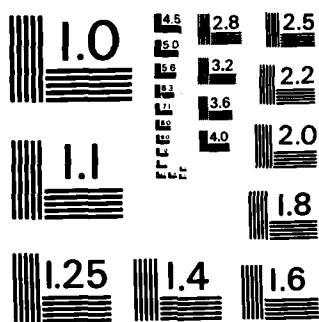
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**FINAL REPORT ON PROJECT NR 150-464
IMPROVED ESTIMATION PROCEDURES
FOR ITEM RESPONSE FUNCTIONS**

by
Robert K. Tsutakawa

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**Research Report-84-2 ✓
OCTOBER 1984**

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes the main findings of a research conducted under ONR contract N00014-81-K-0265, NR-150-464, during the period May 16, 1981 - September 30, 1984. The research focused on the estimation of parametric item response curves under the assumption that univariate ability parameters are sampled from some parametric population distribution. Both maximum likelihood and Bayesian approaches have been studied and compared to the more conventional approaches where abilities are treated as fixed parameters. | | |

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Introduction

The overall objective of the research is to develop new statistical procedures for estimating item response curves used in mental testing. A typical test, which is studied here, consists of K test items administered to n examinees. The data consists of a matrix of binary scores indicating which items are scored correctly and which incorrectly by each of the examinees.

The analysis of such data is based on an assumed model which specifies the probability of correct response to each item as a function of the ability of the examinee. Such probability models can be indexed by item parameters. The main result of this research is the development of new methods for estimating these item parameters for the purpose of measuring abilities based on such estimates.

When abilities are defined in terms of real variables and treated as fixed effects, both theoretical and practical analysis of item responses are greatly hampered by the large number of parameters, which increases as the number of examinees, n , increases. The standard method for simultaneously estimating item and ability parameters is maximum likelihood, using standard programs such as LOGIST described in Wingersky, Barton, and Lord (1982). Some of the problems encountered by this approach are the occasional non-existence of a true maximum likelihood solution and the lack of a reasonable measure of the reliability of the estimated parameters.

The approach taken by the current research assumes that ability parameters are sampled from some population distribution, which itself may be indexed by parameters. The true likelihood function then becomes the integral of the conventional likelihood function with respect to the ability distribution. The resulting likelihood function is then a function of the item parameters and the "hyperparameters" of the unknown ability distribution. Though the resulting expression for the likelihood function is not simple, it contains substantially fewer parameters than the conventional maximum likelihood equations. A general approach to finding the maximum likelihood estimate using the new likelihood function is the EM algorithm, discussed in its general form by Dempster, Laird, and Rubin (1977). However the implementation of the EM algorithm requires heavy computation involving numerical integration. Earlier versions of the EM algorithm are given for the one-parameter logit model by Sanathanan and Blumenthal (1978) and for the two parameter probit model by Bock and Aitkin (1981). Part of the current work is an extension and refinement of these earlier applications.

The main work also includes an extension to fuller Bayesian methods by introducing prior distributions on the item parameters. The EM algorithm can be modified for computing posterior modes. The reciprocal of the negative second derivative of the log posterior evaluated at the mode is then used to approximate the posterior covariance matrix of item parameters. The Bayesian approach gives us a means of posterior analysis and opens up new tools for practical problems such as item selection and adaptive testing.

A brief account of the specific accomplishments of this research are summarized below. Fuller write-ups of the technical details are given in the technical reports and other papers listed at the end of this report.

A. Maximum likelihood (m.l.) estimation of item parameters.

1. General setup.

When the ability parameters are assumed to be a random sample from a distribution with parameter γ , the formal likelihood function $\ell(\xi, \gamma)$ becomes a function of the item parameters ξ and ability distribution parameter γ . Under the assumption of local independence, the EM algorithm has been demonstrated as being a powerful tool for deriving the m.l. estimate, $(\hat{\xi}, \hat{\gamma})$. The computation reduces to working with a series of simpler problems involving one item at a time. For the one parameter logistic with a $N(0, \sigma^2)$ ability distribution, the results are very similar to those obtained by Anderson (1970) using the conditional maximum likelihood approach. Simulation results have shown that estimates usually exist when they do not under the conventional m.l. approach which treats the ability parameter as fixed. Simulations have also suggested that there can be a savings in sample size of 10 - 15% when calibrating items under the one parameter logistic model, relative to the conventional methods. Similar results have been found for ability parameters estimated as posterior means, given $(\xi, \gamma) = (\hat{\xi}, \hat{\gamma})$. Details have been published in Rigdon and Tsutakawa (1983).

2. Convergence of the EM algorithm in item response analysis.

Certain questions concerning the convergence of the EM algorithm have been raised in the recent literature. Convergence is guaranteed for the 1-parameter logistic due to convexity properties of the likelihood function. For the two-parameter logistic it can be demonstrated that the EM solution is the solution to the likelihood equation, so that if there is a unique solution it will coincide with the EM solution. Details are presented in Research Report 82-1.

3. Estimation of 2-parameter logistic curves.

Computational details required in the EM algorithm for the 2-parameter logistic model have been derived and illustrated. The nonuniqueness of the parameterization in the 2-parameter model can be eliminated by placing restrictions on the ability prior. In particular, for normal priors on ability, uniqueness is obtained by using the $N(0,1)$ distribution. The asymptotic covariance matrix of the item parameters can be computed using the empirical information matrix. Numerical results based on simulations have indicated the reasonableness of this approach for assessing the posterior uncertainty of the m.l. estimates. Details are presented in Research Report 83-1.

B. Empirical Bayes estimation of item parameters.

In certain situations the item parameters, in addition to the ability parameters, may be treated as a random sample from some prior distribution indexed by an unknown hyperparameter. This situation arises when the item parameters are exchangeable, and the prior information on each item is the same from item to item. Certain ad hoc procedures have been developed for the 1-parameter logistic model. The basic procedure consists of alternately re-estimating the item and ability parameters, which are assumed to be sampled from separate normal distributions with unknown parameters, until convergence is attained. Results were very similar to those derived under A.1. Due to heavy computational requirements, extensions to multiparameter models were not successful. This part of the work is summarized in Rigdon and Tsutakawa (1984).

C. Bayesian estimation of item response curves.

The third and final estimation procedure developed in this project is a fully Bayesian method based on a new family of prior distributions for the item parameter. This family of priors differs from the one proposed by Swaminathan and Gifford (1981), which assumes that item parameters have a common prior whose hyperparameter has a known distribution. The current approach assumes a prior distribution on the probability of correct responses at specified ability levels, for each item separately. This prior then induces a prior on the item parameters. In applications this approach seems simpler than working through the hyperparameters.

The estimation of item parameters is made by using the posterior mode which can be computed via the EM algorithm. The measure of uncertainty is then taken to be the posterior covariance, which can be approximated by the reciprocal of the negative second derivative matrix of the log posterior. Numerical illustrations for the 2-parameter logistic model have shown that the posterior modes are very similar to the m.l. estimator described under A.2 and these obtained via LOGIST. This illustration was based on a 39 item math test using a sample of 400 subjects. Details are presented in Research Report 84-1.

D. Some unfinished work.

1. Comparison of item response curves.

Two curves can be compared in terms of their logits at different ability levels. In the case of the 2-parameter logistic model, the logits are straight lines. The posterior probability that two such lines are within a given distance over some fixed interval of ability is presented as a measure of the closeness of two lines. This approach differs from the more conventional approach where comparisons are made in terms of the item parameters. Numerical work based on simulated data and actual test data have been completed. Results remain to be written up.

2. Goodness-of-fit study.

A cross validation study was started to examine the predictability of item responses in one data set given observations on a separate but related data set. The test statistics being examined turned out to have power against certain alternative, but not against other alternatives which might be equally important. This phase of the research was discontinued pending a better test statistic.

E. Summary

This research has demonstrated that estimation of item curves with ability parameters treated as a random sample is a promising important approach to item response analysis. Although such modelling has been considered in the past, practical solutions have only recently become a reality with the advent of modern computer technology and the EM algorithm.

This research has focused on the theoretical formulation and solution of maximum likelihood and Bayesian estimations of item parameters. Algorithms have been developed and numerically illustrated for the one and two parameter logistic models. The results are generally comparable to the conventional methods which treat ability parameters as fixed. The current methods have the advantage however of generally producing estimates when they do not exist under older methods. The Bayesian approach yields an approximation to the posterior covariance matrix, which can be used to make probabilistic statements about the uncertainty of the estimated parameters.

Before widespread applications of these results can be realized, it is important that user oriented computer packages be prepared. Such packages should not only handle the case of n subjects and K items, but must be able to deal with missing data and other designs where different subjects may be given different items, as in the case of adaptive testing. For such packages, it would be desirable to include the 3-parameter logistic model, since guessing is an avoidable problem with tests using the multiple choice format which is quite commonly used today.

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